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The objective was to investigate theoretically as well as experimentally the ion-exchange process and solgel technology for fabrication of passive integrated optical circuits in glass for signal processing applications.
The study performed during the period involved several sub-projects: 1) Passive, low-loss waveguides and tapers by Ag^+ - Na^+ exchange, 2) Surface and buried channel waveguides by K^+ $-Na^+$ exchange, 3) Fabrication and characterization of 3 dB cross-couplers, 4) Laser-assisted fabrication of waveguides in gel-silica.

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Final Technical Report

Grant #AFOSR-88-0199

Period: 01 May 1988 - 30 April 1989

INTRODUCTION

The primary object of the project is to investigate theoretically as well as experimentally the ion-exchange process and solgel technology for fabrication of passive integrated optical circuits in glass for signal processing applications. The study was originally initiated through an Air Force Contract (No. F 08635-83-K-0263) in 1983, then funded by AFOSR Contract No. 84-0369 from 1984 to 1988. At the end of the contract No. 84-0369, we provided an extensive report of the work performed until February 1988. The present report deals with the progress made in both the ion-exchange and the gel-silica waveguide technology during the period May 1988-April 1989 covered by grant #AFOSR-88-0199.

The study performed during the period involved several sub-projects.

1. Passive, low-loss waveguides and tapers by Ag^+-Na^+ exchange.
2. Surface and buried channel waveguides by K^+-Na^+ exchange.
3. Fabrication and characterization of 3 dB cross-couplers.
4. Laser-assisted fabrication of waveguides in gel-silica.

In the following we describe the work performed in each of the above areas and refer to the six publications for details. Copies of the publications are attached along with this report as an Appendix.

1. Ag^+-Na^+ Waveguides and Tapers

In the previous report we demonstrated single mode, buried waveguides using two-step Ag^+-Na^+ exchange. As a result, fiber-compatible mode sizes were achieved and the surface-scattering was substantially reduced. However, the propagation losses in the commercial soda-lime glass substrates were still unacceptable viz., 0.6 dB/cm. Since then we have concentrated our efforts to simplify the process and reduce the losses. In one approach [1], the process simplification was achieved by employing a one-step electromigration technique which uses a silver film as the ion source. In another approach [2,3], the losses were lowered by using optical quality BK7 glass substrates and performing a postbake procedure on the surface channel waveguides fabricated from $AgNO_3$ + $NaNO_3$ melts.

The electromigration technique has several advantages:

1. The side diffusion which occurs under metallic masks in diffusion from molten salts is prevented when silver film is used. The side diffusion in the former case has been attributed to the presence of electrochemical potential gradients between the metallic mask, the glass, and the melt. The effect has been reduced by using insulating masks but has not been eliminated completely. When silver strips are used, the electromigration takes place from the metallic films and the lateral migration of silver ions is reduced. However, the thermal diffusion is always present and as a result, the mode size of the waveguide increases with the buried depth. This would limit the extent to which the channels can be buried to about 5 μm if the compatibility with fibers is to be maintained.
2. The process is relatively simple and buried waveguide is obtained in a single-step process at relatively low temperatures. This is a significant improvement over the conventional two step process where the diffusion is first performed in a molten salt mixture, e.g., $AgNO_3$ + $NaNO_3$ at elevated temperature to obtain the surface waveguide. A second-step electromigration from pure $NaNO_3$ is then necessary to bury the waveguide. This involves cooling the waveguide back to room temperature, cleaning, replacement of the salt, and subsequent ion exchange at higher temperature.

3. In addition, there is no need to deposit gold electrodes on the silver films since molten salt baths serve as the electrodes. This eliminates an expensive processing step used in the previous fabrication process. Besides using the silver film as the ion source, we have extended the melt-source technique developed during the past four years to new glasses and fabricated low-loss devices.

To reduce the propagation losses, we used optical quality BK7 glass as the substrate material. Its composition is listed in Table I

Table I: BK7 composition by wt%

SiO_2	69.6
B_2O_3	9.9
Na_2O	8.4
K_2O	8.4
BaO	2.5
Traces	1.2

In order to get fiber compatible surface-index change ($\Delta n \sim 0.01$), the mole fraction of $AgNO_3$ in the $NaNO_3$ melt was kept at 1×10^{-3}. A systematic study of planar and surface channel waveguides was subsequently performed to define appropriate diffusion parameters [2,3]. It was observed that the surface guides exhibit large insertion losses. However, when these guides were postbaked in the ambient, the [illegible]sses were reduced to about 0.2 dB/cm, on the average. Moreover, the mode [illegible] was enlarged so as to become fiber compatible although slight [illegible]metry results from the fact that these are still surface waveguides. [illegible]duction in insertion losses occurred when postbaking was substitute[illegible] the surface guides in silver-free melt. Using this techni[illegible] [illegible]bricated waveguides with total fiber-guide insertion losses be[illegible] 15 mm long devices by Ag^+-Na^+ exchange in BK7 glass [3]. These figures are the lowest reported in the literature.

A technique was developed to fabricate tapered transitions in waveguides in BK7. Both extremeties were tapered by placing the surface straight channel guides in a furnace with suitable temperature gradient. This is equivalent to postbaking and gives rise to tapered cross-sections. Near-adiabatic tapers have been produced using this technique [3].

2. K^+-Na^+ exchanged waveguides

We have performed a detailed and systematic study of this cation pair in soda-lime as well as BK7 glass [4]. K^+-Na^+ system seems to be very attractive for fabrication of waveguides with reproducible characteristics since the process is characterized by small diffusion rates which translates into better control of the diffusion depth. Moreover, the ion source is generally a molten bath of pure KNO_3 where the control of K^+ ions is easier to achieve. Another advantage of K^+-Na^+ exchange is the relatively smaller Δn (0.008-0.009) that is compatible with single-mode fibers.

The systematic investigation K^+-Na^+ exchanged guides performed during this period permitted a deeper understanding of the role of the processing conditions and the substrate glass in influencing the index profile of planar, surface, and buried waveguides. An electron microprobe was used to measure the potassium concentration profile and the data were correlated with the index profile derived from the mode-index characterization and with the diffusion profile calculated by solving the diffusion equation. The index profile for the case of planar waveguides was examined in detail for soda-lime silicate and BK7 glasses and was observed to be Gaussian and ERFC, respectively, in agreement with earlier reports in similar glasses. The differences are attributed to the large disparity in the sodium/potassium ion mobility ratio in the two glasses, and it is not necessary to invoke an outdiffusion of the alkaline earth ions in BK7 to explain the index profile as was assumed by other workers. The surface-index change was measured as a function of the melt composition and was observed to vary nonlinearly with the melt concentration of potassium ions, a result in sharp contrast to the linear behavior reported earlier in another glass. The results on the surface-index change are explained on the basis of stress-induced effects in soda-lime glass. However, in BK7 some discrepancies still exist in explaining the magnitude of the net index change. Moreover, the stress models proposed so far do not really explain the magnitude of the observed birefringence in both the glasses. The mobility of the K^+ ions was estimated by determining the diffusion depth of planar surface waveguides fabricated by electromigration. A variation of the ionic current was observed (an almost exponential decrease in soda-lime glass and almost no change in BK7), and the behavior was explained on the basis of the double-alkali effect in both the glasses. Using a two-step process, buried channel waveguides for operation at 1.3 μm were fabricated in both the glasses with nearly circularly symmetric near-field intensity profiles. Record low-loss waveguides with insertion loss of less than 1.0 dB in 20 mm long devices were obtained using the two-step process in BK7 glass. Depolarization of surface channel waveguides was measured and found to be less than 0.7 percent for 20 mm long samples. However, there are a few issues which need further attention. Unlike Ag^+-Na^+ waveguides where the diffusion depth of channel regions increases monotonically with diffusion time, the K^+-Na^+ channel waveguide depths show a saturation at ~ 7 μm. This behavior is not well understood and further work is necessary to overcome the depth limitation. Similarly, we still do not adequately understand the stress-induced effect and its influence on the index change. While a reasonable agreement was obtained in soda-lime glass, a large discrepancy in

BK7 still remains to be explained.

3. Cross-couplers

We have designed and fabricated 3 dB single-mode cross-couplers in Ag^{+}-Na^{+} ion-exchanged BK7 glass [5]. The analysis was performed using the normal mode propagation method to determine the characteristics of a graded-index slab waveguide structure which simulates the effective index profile of our channel waveguide devices. The adiabatic condition (which guarantees minimal normal mode conversion along the propagation direction) was determined and several couplers were fabricated using asymmetric-symmetric 2x2 structure. The measured results demonstrate a 50:50 power split ratio when either input guide is excited. Furthermore, the device is fiber compatible, polarization independent and wavelength insensitive. Losses as low as 2.5 dB in 50 mm long devices are easily achieved [5].

4. Laser-Assisted Gel-Silica Waveguide Fabrication

We have studied laser-induced densification in gel-silica glasses for waveguide fabrication [6]. It has been shown by Dr. L. L. Hench and co-workers at the University of Florida that gel-silica produced by sol-gel process is an attractive host as well as a substrate material for a variety of integrated optical and opto-electronic devices. With sufficient control of the kinetics and the ultra-structure, it is possible to achieve optical transparency which is superior to that of commercial optical silica in the 300-3500 nm spectral region. Partially densified gel is obtained as an intermediate product in the processing steps to obtain fully densified silica. The refractive index and density of the porous silica depends on the densification time and temperature. Upon subjecting the partially dense substrates to a secondary heat treatment, further densification occurs as a result of out diffusion of the pores. It is this behaviour which was exploited in our laboratory for the first time to fabricate optical waveguides by laser-induced local heating. The technique consists of focussing the TEM_{00} beam of a CO_2 laser (λ = 10.6 μm) at the sample surface and scanning the irradiated zone by a computer-controlled x-y stage. The reflected CO_2 beam power is measured to monitor the degree of densification. The waveguides were characterized for the index-change, surface profile, cross-sectional dimensions, and attenuation. It appears that the best starting density is 2.0 which corresponds to a substrate refractive index of 1.44. However, there are serious problems in reproducing substrate samples of the above characteristics. Efforts are underway to overcome these problems and are subject of the research project of Professor L. L. Hench, under contract from AFOSR.

Publications (May 1988 - April 1989)

1. "Single-mode buried channel waveguide by one-step electromigration from silver films", H. Zhenguang, R. Srivastava and R. V. Ramaswamy, Appl. Phys. Lett. Vol. 53, pp 1681-1683, 31 Oct. 1988.

2. "Low-loss nearly adiabatic passive waveguide tapers", H. Zhenguang, R. Srivastava and R. V. Ramaswamy, Topical Meeting on Integrated and Guided Wave Optics (Optical Society of America), Houston, TX, Feb. 1989. Paper TuBB3.

3. "Passive low-loss small-mode waveguides and near adiabatic tapers in BK7 glass," H. Zhenguang, R. Srivastava and R. V. Ramaswamy, Accepted for publication in IEEE J. Lightwave Tech.

4. "Fiber-compatible K^+-Na^+ ion exchanged channel waveguides: fabrication and characterization", A. Miliou, H. Zhenguang, H. C. Cheng, R. S. Srivastava and R. V. Ramaswamy. Accepted for publication in IEEE J. Quantum Electron. QE-25, August 1989.

5. "Single-mode cross coupler 3 dB power dividers by ion-exchange", C. P. Hussell, H. C. Cheng, R. Srivastava, R. V. Ramaswamy and J. L. Jackel, to be presented at Second Microoptics Conference/Eighth Topical Meeting on Gradient-Index Optical Imaging Systems (MOC/GRIN '89), Tokyo, July 1989.

6. "Laser-assisted fabrication of optical waveguides in gel-silica glasses", A. Miliou, R. Srivastava, R. V. Ramaswamy, R. W. Slocumb, T. Chia and J. West, Topical Meeting on Integrated and Guided Wave Optics (Optical Society of America), Houston, TX, Feb. 1989, Paper Tu BB1.

Appendix

Publications
(May 1988 - April 1989

AFOSR Contract